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The first of four North American Ice Ages commenced about 2.8 m.y. ago, reached a maximum between 2.4 and 2.6 m.y. ago during which continental glaciers invaded southwestern Iowa and southeastern Nebraska, and ended about 2.1 m.y. ago. This first Ice Age may span the Pliocene-Pleistocene boundary herein placed at 2.5 ± 0.1 m.y. The second Ice Age occurred about 1.9 to 1.5 m.y. ago. However, apparently it was not severe enough for glaciers to reach into Nebraska or central Iowa. The third Ice Age occurred between about 1.0 and 0.4 m.y. ago. Glaciers invaded Nebraska and Iowa at least four times during this Ice Age, and periods between these advances were of sufficient duration for the formation of paleosols and gleys. The classic Nebraskan-Aftonian-Kansan sequence was deposited during this Ice Age. The fourth Ice Age commenced about 100,000 years ago. Deposits representing this Ice Age reached central Iowa but apparently did not enter Nebraska.

Conceptual application of the classic North American Pleistocene stage terms has resulted in the stages having overlapping time spans. In view of this and because $\simeq$ 60 percent of the Pleistocene is pre-Nebraskan, the classic stage terms need to be revised or abandoned.

Interpretations of events leading up to the Ice Ages in Nebraska have previously been based on faunas and sediments from what was considered a relatively complete sedimentary and faunal sequence spanning late Pliocene and early Pleistocene time (the "Kimballian fauna" from the uppermost Ogallala Group and the Broadwater Formation and fauna, respectively). Data presented here indicate these sediments and faunas are separated in time by about 4 m.y., and the significance of the marked differences between "Kimballian" and Broadwater faunas needs re-evaluation.

† † †

INTRODUCTION

This report is based primarily on fission-track ages of volcanic ashes, studies of glacial deposits, and physical stratigraphy in Nebraska, western Iowa, southeastern South Dakota, and portions of Kansas and Texas. This report updates and summarizes earlier reports (Boellstorff, 1973, 1976, 1977a); the reader may want to refer to these reports for details and methodology. Although this summary deals principally with the chronology of late Cenozoic deposits from portions of the midcontinent, data from the Gulf of Mexico and Italy are also incorporated.

PLIOCENE-PLEISTOCENE BOUNDARY

The working group of the International Geological Correlation Program-Project (IGCP) N 41 "Neogene-Quaternary Boundary" and the Subcommission on the Plio-Pleistocene Boundary of the International Union on Study of the Quaternary (INQUA) are considering a section near Vrica, about 4 km south of Crotone, Italy, as a potential stratotype for the Pliocene-Pleistocene boundary. Furthermore, these groups stated, "This boundary can be defined by the appearance of cold-water North Atlantic immigrants in the Plio-Pleistocene sequence of Calabria." (Resolution of the joint meeting of the INQUA subcommission on the Plio-Pleistocene boundary and the IGCP working group on the boundary between the Neogene and Quaternary held in Birmingham, England, 1977.)

Volcanic ash occurring about 25 meters above the recommended base of the Pleistocene in the Vrica section yielded a fission-track age of 2.5 ± 0.1 m.y. (millions of years before present) (Boellstorff, 1977b). Considering the very high sedimentation rate of 35 to 60 cm/1000 years in the Vrica area during the Upper Pliocene and Early Pleistocene (Selli, et al., in press) and the fact that the dated ash occurs about 25 meters above the recommended boundary, perhaps 40,000 to 70,000 years should be added to the 2.5 ± 0.1 m.y. date.

However, because the ± 0.1 m.y. error associated with the Vrica ash date includes the 40,000 to 70,000 years for sedimentation of the 25 meters below the ash, the 2.5 ± 0.1 m.y. date is herein used as a tentative minimum age for the Plio-Pleistocene boundary.

CHRONOLOGY OF DEPOSITS REPRESENTING THE ICE AGES IN THE CENTRAL UNITED STATES

Methodology

Studies of the makeup of glacial deposits, ages of volcanic ashes, and physical stratigraphy in western Iowa, eastern Nebraska, and southeastern South Dakota have provided data permitting the formulation of an approximate chronology for deposits representing the Ice Ages in this area (Boellstorff, 1973, 1976, 1977a). In conjunction with the most recent of these studies, glacial deposits were sampled at 30 localities—1 in southeastern South Dakota, 16 in eastern Nebraska, and 13 in western Iowa (Fig. 1 and Table I). The entire glacial sequence present at each locality was sampled except at the Murray Hill, Iowa, locality where the full thickness is not completely exposed. At seven of the localities, samples were taken from outcrops. The other 23 localities were sampled predominantly by continuous coring with the use of a Failing model-750 drilling rig and a 10-foot core barrel which cut a 2 1/8 inch core. Approximately 4,800 feet were drilled, with about 3,500 feet being cored.

The sampled localities included many of the sites where interpretations of stratigraphic relationships have played an important role in the development of the classification of Pleistocene deposits in the study area and beyond. Among the localities were the type area of the Nebraska Till of Schimek (1909) near Florence, Nebraska; the Kansan-Aftonian-pre-Kansan sequence of Bain (1896) and Chamberlin (1896) near Afton, Iowa; the Little Sioux or Harrison-Monona County Line Section near Little Sioux, Iowa; and the type localities of the Elk Creek, Nickerson, Cedar Bluffs, Clarkson, Santee, and Hartington Tills of Reed and Dreeszen (1965) in eastern Nebraska.

Analyses of till composition consisted of the following: determination of heavy-mineral types (Sp. Gr. > 2.85) in the very fine sand fraction; (0.062–0.125 mm) rock types in the $>$ 4 mm pebble fraction; and the percentages of calcite and dolomite in the till matrix. Normally, alternate 5-foot intervals of till were analyzed, and three or more analyses were made on each till present at each locality.

Heavy minerals were separated by using bromoform and were classified by using a polarizing microscrope into these categories: hornblende, mica, garnet, epidote, opaque minerals, and unidentified. Pebbles were handpicked from disaggregated, air-dried till samples, and those larger than 4 mm in diameter were separated from smaller pebbles by sieving. A binocular microscope was used in identifying the pebbles. Limestone and dolomite pebbles were distinguished by their reaction to acid. The pebbles were categorized as follows: limestone, dolomite, chalk, calcareous grit, total calcareous pebbles, noncalcareous grit, ferruginous siltstone and sandstone, quartz, chert, shale, total sedimentary pebbles, quartzite, greenstone, metawacke, total metamorphic pebbles, granite, and total plutonic pebbles.

Percentages of calcite, dolomite, and total carbonate in the till matrix were determined by using a Chittick apparatus and by following the procedure outlined by Dreimanis (1962). Two analyses were made on each sample, and the results averaged.

The results of multiple determinations of heavy-mineral, pebble-type, and calcite-dolomite percentages for each till at each locality were reduced to an average for each till unit at each locality. This resulted in a set of 27 values for each till at each locality (including the combined percentages of opaque minerals and sedimentary pebbles). In all, 60 such sets were obtained in this study. These data were subjected to graphical, Q-mode factor, cluster, and principal-component analyses in an attempt to decipher till groupings.

Volcanic ashes associated with the glacial deposits in the study area were dated by using the fission-track technique on glass shards as described by Boellstorff and Steineck (1975) and in more detail by Boellstorff (1976).

Results and Discussion

As shown in Figures 2 and 3, graphical and Q-mode factor analyses of the till composition data reveal three compositional groups—here merely labeled A, B, and C. The data points in the graph showing the combined percentages of sedimentary rock pebbles and opaque heavy minerals in relation to the combined percentages of non-sedimentary pebbles, hornblende, biotite, and garnet correspond with those in the graph showing factor I in relation to factor II, based on all 27 variables (Figs. 2 and 3). This correspondence indicates that the percentages of hornblende, biotite, garnet, and opaque minerals in the very fine sand fraction along with the percentages of sedimentary and non-sedimentary pebbles in the $>$ 4 mm fraction are sufficient to differentiate tills belonging to group A, B, or C.

Conclusions based on the studies of tills and volcanic ashes in the study area are shown in Figure 4 and summarized below.

Group C—the oldest tills—represents at least two glacial advances. These tills are characterized by a very high percentage (generally 90 percent) of sedimentary rock pebbles

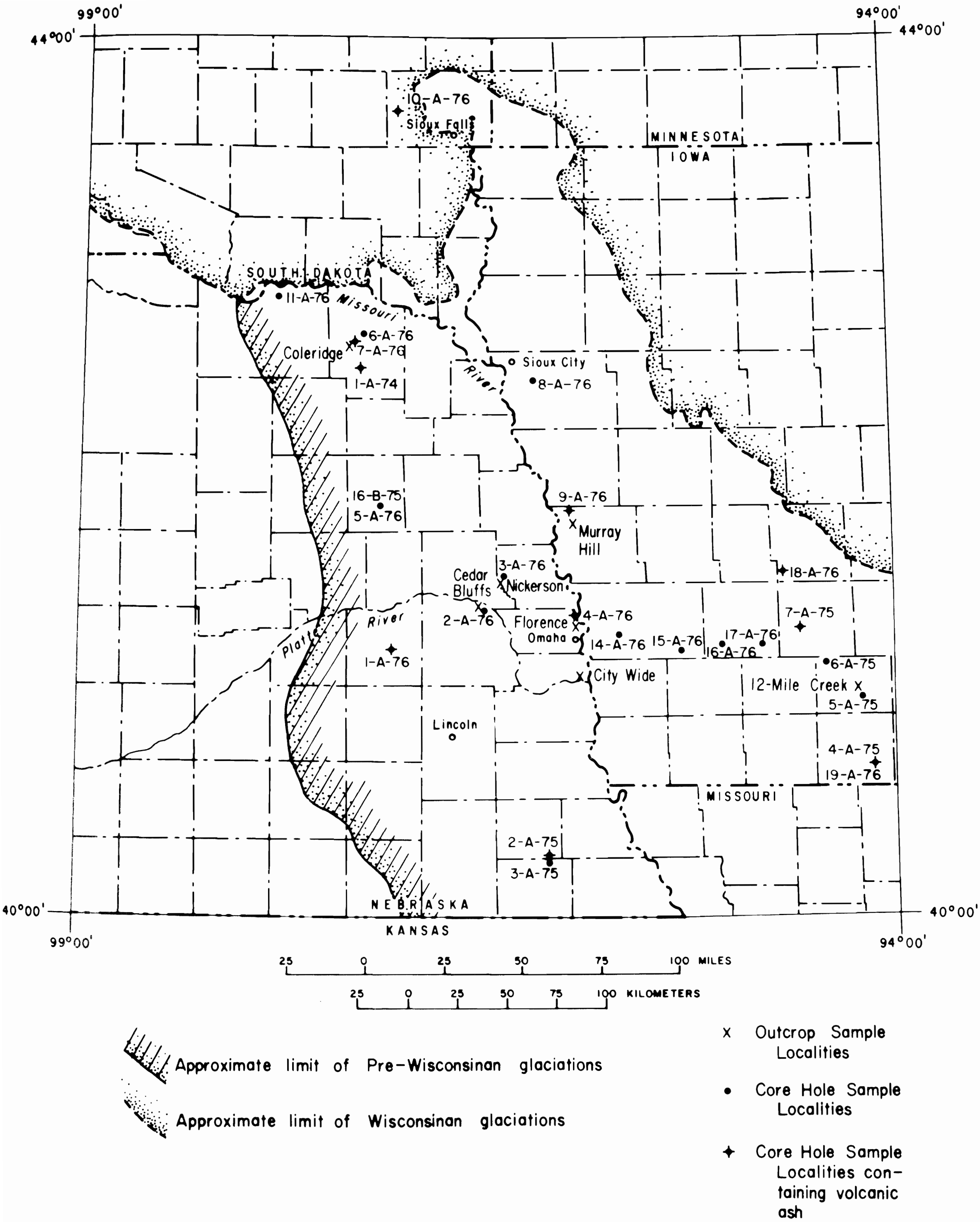

Figure 1. Sample localities. See Table I for legal descriptions.

TABLE I

Sample Localities

1-A-74	Test hole, NE NW NE NE NW sec. 4, T. 30 N., R. 1 E., Cedar County, Nebraska. (Hartington ash locality.)
16-B-75	Test hole, NW corner NE sec. 36, T. 22 N., R. 2 E., Stanton County, Nebraska. (Type locality of the Clarkson Till of Reed and Dreeszen, 1965.)
2-A-75	Test hole, SE corner SW sec. 26, T. 4 N., R. 11 E., Johnson County, Nebraska. (Elk Creek volcanic ash site.)
3-A-75	Test hole, SE corner NE SE sec. 2, T. 3 N., R. 11 E., Pawnee County, Nebraska. (Type locality of Elk Creek Till of Reed and Dreeszen, 1965.)
4-A-75	Test hole, NW corner NE NE sec. 19, T. 68 N., R. 28 W., Ringgold County, Iowa. (Mt. Ayre, Iowa, volcanic ash site.)
5-A-75	Test hole, NE NW NW sec. 33, T. 72 N., R. 29 W., Union County, Iowa. (Type area of Kansan and pre-Kansan tills of Bain 1896, and Chamberlin, 1896.)
6-A-75	Test hole, SE SW SW sec. 3, T. 73 N., R. 31 W., Union County, Iowa.
7-A-75	Test hole, SE NE SW SE sec. 18, T. 75 N., R. 32 W., Adair County, Iowa. (Fontanelle volcanic ash site.)
1-A-76	Test hole, NW corner SW SW SW sec. 33, T. 15 N., R. 3 E., Butler County, Nebraska. (David City volcanic ash site.)
2-A-76	Test hole, NE NE NW sec. 33, T. 17 N., R. 8 E., Saunders County, Nebraska. (Type area of Cedar Bluffs Till of Reed and Dreeszen, 1965.)
3-A-76	Test hole, SW NE SE sec. 8, T. 18 N., R. 9 E., Washington County, Nebraska. (Type area of the Nickerson Till of Reed and Dreeszen, 1965.)
4-A-76	Test hole, NW NW NE SW sec. 9, T. 16 N., R. 13 E., Douglas County, Nebraska. (Hummel Park Section, type area of the Nebraskan Till of Shimek, 1909.)
5-A-76	Test hole, NW corner NE sec. 36, T. 22 N., R. 2 E Stanton County, Nebraska. (Type locality of th Clarkson Till of Reed and Dreeszen, 1965.)
6-A-76	Test hole, NE NW NW NW sec. 24, T. 31 N., R. E., Cedar County, Nebraska. (Type locality of th Hartington Till of Reed and Dreeszen, 1965.)
7-A-76	Test hole, SE SW SW sec 11, T. 29 N., R. 1 E Cedar County, Nebraska. (About 1.25 miles SW Coleridge volcanic ash site.)
8-A-76	Test hole, NW NE NE sec. 34, T. 88 N., R. 46 W Woodbury County, Iowa.
9-A-76	Test hole and outcrop SE NW sec. 5, T. 81 N., 44 W., Harrison County, Iowa. (Little Sioux Harrison-Monona County line locality.)
10-A-76	Test hole and outcrop, NE SW NE sec. 11, T. 10 N., R. 51 W., Minnehaha County, South Dakot (Hartford Section.)
11-A-76	Test hole, SE SE NW sec. 29, T. 33 N., R. 4W Knox County, Nebraska. (Type locality of Sante Till of Reed and Dreeszen, 1965.)
14-A-76	Test hole, SW SW NW SW sec. 9, T. 75 N., R. 4 W., Pottawattamie County, Iowa. (No till at th site.)
15-A-76	Test hole, SW corner SE sec 27, T. 74 N., R. 39 W Pottawattamie County, Iowa.
16-A-76	Test hole, NE NW sec. 26, T. 74 N., R. 37 W., Ca County, Iowa.
17-A-76	Test hole, NE NW NW NW sec. 8, T. 74 N., R. 3 W., Cass County, Iowa.
18-A-76	Test hole, SE SE sec. 8, T. 78 N., R. 33 W., Guthri County, Iowa. (Guthrie volcanic ash site.)
19-A-76	Test hole, NW corner NE NE sec. 19, T. 68 N., 28 W., Ringgold County, Iowa, volcanic ash site.)

Murray Hill Section, road cut in bluffs along east side of Missouri River Valley, NW NW NW sec. 17, T. 81 N., R. 44 W., Harriso County, Iowa.

City Wide Rock Quarry Section, NE NW sec. 29, T. 13 N., R. 13 E., Sarpy County, Nebraska.

Type locality of the Nickerson Till of Reed and Dreeszen, 1965; SE SW sec. 8, T. 18 N., R. 9 E., Washington County, Nebrask

Type locality of the Cedar Bluffs Till of Reed and Dreeszen, 1965; SW NE NW sec. 24, T. 17 N., R. 7 E., Saunders County, Ne braska.

Coleridge Volcanic Ash site; NW NE NE sec. 11, T. 29 N., R. 1 E., Cedar County, Nebraska.

Type locality of the Nebraskan Till of Shimek, 1909, north of Florence, Nebraska; center SW sec. 16, T. 16 N., R. 13 E., Dougl County, Nebraska.

Type area of the Kansan and preKansan tills of Bain, 1896, and Chamberlin, 1896, south of the Twelvemile Creek, SW NW sec. 2 T. 72 N., R. 29 W., Union County, Iowa. The presence of Kansan Till over Aftonian interglacial deposits over Nebraskan Till wa described at or near this locality by Kay and Apfel, 1929.

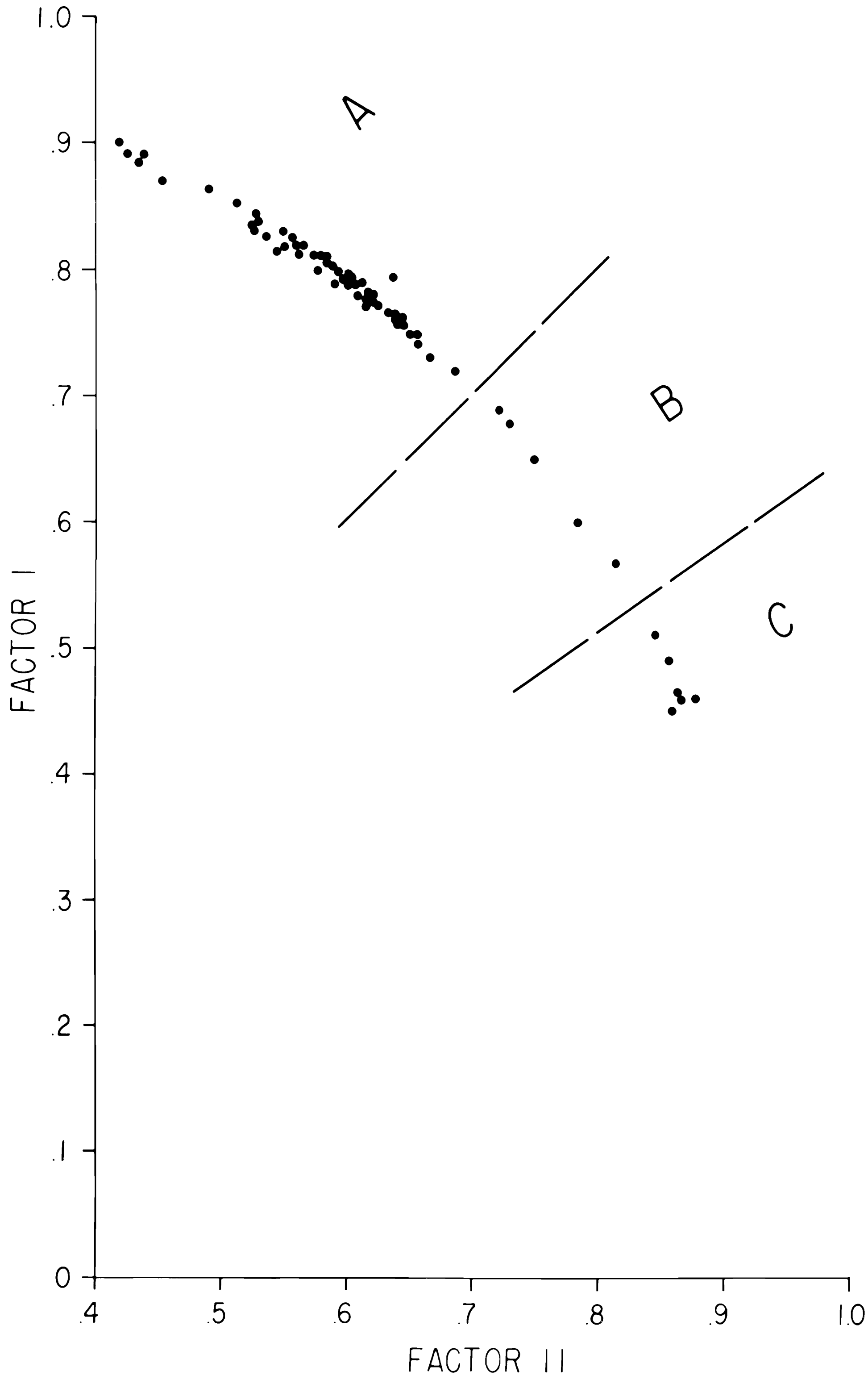

Figure 2. Compositional groupings of tills based on Q-mode factor analysis of heavy mineral, pebble-type, and calcite-dolomite data. Capital letters refer to the compositional groups described in text and shown in Figures 3 and 4. The points in each group in this figure fall into the corresponding groups in Figure 3.

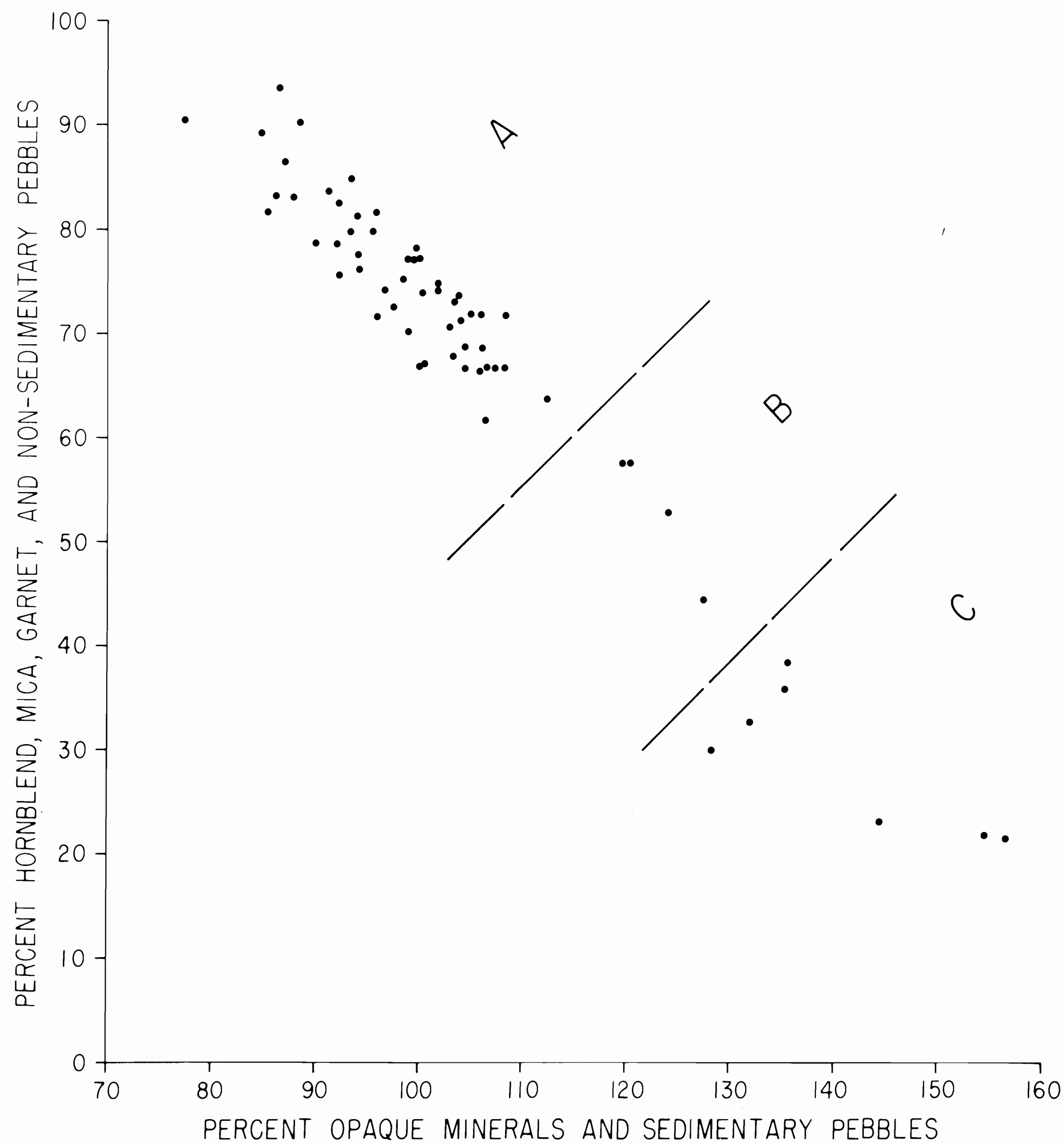

Figure 3. Compositional groupings of tills based on relationships of selected heavy mineral and pebble-type data from tills in Iowa, Nebraska, and South Dakota. Capi-

Remarks	City Wide Quarry, Sarpy County, Nebraska	2-A-75 Johnson County, Nebraska	3-A-75 Johnson County, Nebraska	4-A-75 19-A-75 Ringgold County, Iowa	5-A-75 Union County, Iowa	6-A-75 Union County, Iowa	7-A-75 Adair County, Iowa	1-A-76 Butler County, Nebraska	2-A-76 Saunders County, Nebraska	3-A-76 Washington County, Nebraska	4-A-76 Douglas County, Nebraska	5-A-76 16-B-76 Stanton County, Nebraska	6-A-76 Cedar County, Nebraska	7-A-76 Cedar County, Nebraska
Type Clarkson Till of Reed and Dreeszen, 1965; Illinoian Till of Flint, 1955; Kansan Till of Bain, 1896, and Chamberlin, 1896, normal polarity		-0.6-		A -0.6-	A	A	A -0.7-				-0.7-	A		
Type Cedar Bluffs Till of Reed and Dreeszen, 1965, normal polarity				A		A	A		A	A		A		
Type Hartington, Nickerson, and Santee Tills of Reed and Dreeszen, 1965, normal polarity			A	A		A			A	A		A	A	A
Prekansan Till of Bain, 1896, and Chamberlin, 1896; Nebraskan Till of Shimek, 1909, reversed polarity	A				A			A			A			
Unnamed Till	B							B						
					-2.2-			-1.2-						-1.2-
Elk Creek Till of Reed and Dreeszen, 1965	C C	C	C C											

Remarks	8-A-76 Woodbury County, Iowa	9-A-76 Harrison County, Iowa	10-A-76 Minnehaha County, So Dakota	11-A-76 Knox County, Nebraska	15-A-76 Pottawattamie County, Iowa	16-A-76 Cass County, Iowa	17-A-76 Cass County, Iowa	18-A-76 Guthrie County, Iowa	Murray Hill, Harrison County, Iowa	12-Mile Creek, Union County, Iowa	Florence, Douglas County, Nebraska	Cedar Bluffs, Saunders County, Nebraska	Nickerson, Washington County, Nebraska	Coleridge, Cedar County, Nebraska
Type Clarkson Till of Reed and Dreeszen, 1965; Illinoian Till of Flint, 1955; Kansan Till of Bain, 1896, and Chamberlin, 1896, normal polarity		-0.7-	A -0.7-				A							
Type Cedar Bluffs Till of Reed and Dreeszen, 1965, normal polarity			A			A	A	A	A	A		A	A	
Type Hartington, Nickerson, and Santee Tills of Reed and Dreeszen, 1965, normal polarity	A	A	A	A	A	A	A	A		A	A	A	A	A
Prekansan Till of Bain, 1896, and Chamberlin, 1896; Nebraskan Till of Shimek, 1909, reversed polarity														
Unnamed Till					B				B					
Elk Creek Till of Reed and Dreeszen, 1965							C							

Figure 4. Till correlations based on compositional groupings, volcanic ash dates, and stratigraphy. The numbers such as –0.7– show volcanic ash dates and positions.

mostly locally derived, and by a very low percentage of hornblende. Near Afton, Iowa (test hole 5-A-75; see Fig. 1 and Table I for location), a Group C till is overlain successively by an accretion gley, a thin ash or ashy silt, and the classic Kansan-Aftonian-pre-Kansan (Nebraskan) sequence. The ash was dated at 2.2 m.y. (± 0.2 m.y., estimated). Stratigraphic relationships show that the Group C till near Afton is older than the pre-Kansan drift of Bain (1896) and Chamberlin (1896) and also older than the Nebraskan drift of Shimek (1909). The composition of the Group C till near Afton, Iowa, indicates correlation with the older of the two Group C tills exposed in the City Wide Quarry in Sarpy County, Nebraska. Although Reed and others (1966) correlated the older till at the quarry with the type Elk Creek Till of Reed and Dreeszen (1965), I am now uncertain which of the two Group C tills at the quarry correlates with the Elk Creek Till at its type locality.

Group B, younger than Group C and older than Group A tills, represents, so far as presently known, only one glacial advance. Its composition is intermediate between that of the other two groups. Test hole 1-A-76 near David City, Nebraska, first penetrated a Group A till, then the Group B till, and then an ash layer that dated at 1.2 ± 0.2 m.y. As indicated in Figure 4, the Group B till also was penetrated by test hole 15-A-76 in Pottawattamie County, Iowa, and is exposed at the City Wide Quarry in Sarpy County, Nebraka, and in the Murray Hill Section in Harrison County, Iowa. The Group B till is not correlatable with any named till and for the present is regarded as unnamed. An ash (Coleridge ash, see Table II for ash nomenclature) of about the same age and similar chemistry as that beneath the Group B till in test hole 1-A-76 occurs in outcrop near test hole 7-A-76 in Cedar County, Nebraska, and is directly overlain by a Group A till. The Group B till is not present at that location. Another occurrence of an ash of about the same age and similar chemistry is in the Sappa Formation at the type location in Harlan County, Nebraska. The Sappa Formation was formerly considered late Kansan or early Yarmouthian in age (Frye, et al., 1948; Reed and Dreeszen, 1965).

Group A—the youngest tills—represents at least four glacial advances based on physical stratigraphy and paleomagnetics. These tills have similar compositions, all being relatively rich in non-sedimentary pebbles and hornblende. Furthermore, nearly all the sedimentary pebbles in Group A tills are derived from non-local sources. One or more tills of Group A are present at all of the localities (Fig. 4). Two Group A tills were encountered at nine localities and three were encountered at four localities. The three Group A tills exposed along Skunk Creek near Hartford, South Dakota (same location as test hole 10-A-76) are paleomagnetically normal; whereas, at three other localities a reversed Group A till is present. Thus, there are at least four Group A tills.

Volcanic ashes dating at about 0.6 m.y. ± [Pearlette ash (restricted)] and about 0.7 m.y. (Hartford ash) both occur in the interval between the deposition of the upper two Group A tills. Thus it appears that Group A consists of three tills definitely younger than 1.2 m.y. but older than about 0.7 m.y. and at least one till younger than about 0.6 m.y. (Fig. 4). The classic Kansan Till appears to be the uppermost Group A till and is younger than about 0.6 m.y. The Nebraskan Till of the Afton, Iowa, area and Shimek's type Nebraskan are both paleomagnetically reversed and are probably the oldest of the Group A tills. I estimate the age of this reversed Group A till to be between about 1.0 m.y. and 0.8 m.y. The classic Aftonian deposits contain both the 0.6 m.y. and 0.7 m.y. ashe and spans at least 100,000 years.

Correlation of the Midcontinent and Gulf of Mexico Records

As shown in Figure 5, there appears to be a close correlation between the chronology of paleotemperatures recorded in the more continuous marine sedimentary sequence of the Gulf of Mexico (Beard, 1969) and the chronology of glacial and nonglacial conditions recorded in the discontinuous continental sedimentary sequence from the midcontinent.

The interpretation of the paleotemperature record from the Gulf of Mexico has been modified in this report. One of the modifications deals with the age of the Brunhes-Matuyama Paleomagnetic Boundary. This boundary now appears to be at least 0.74 m.y. old because ashes dating at about 0.74 m.y. (fission-track, glass) in the study area exhibit normal polarity and may be as old as 0.84 m.y. as indicated by fission-track dates (glass) of 0.84 m.y. from the normally magnetized Bishop Tuff from the "Tom's Place" locality, Mono County, California. In this report, the point representing 0.69 m.y. on Beard's (1969) paleotemperature curve is placed at about 0.8 m.y. The other modification is the addition of a line indicating the approximate level of coldness required for continental glaciers to reach latitudes south of about 41°30′ south. The position of this line is based on the most intense cold of the Wisconsin, recognizing that the study area is just beyond the limits of Wisconsinan glaciation (Fig. 1). These modifications removed two serious problems that were otherwise present in correlating the midcontinent record with the Gulf of Mexico record. The first of these problems was the indication of continental glaciation between about 1.8 and 1.5 m.y. ago, based on the Gulf of Mexico record; whereas, continental glacial deposits dating between 1.2 and 2.2 m.y. are not known to exist in the midcontinent (Fig. 5). The second problem was the interpretation of continental glacial conditions in the midcontinent between 0.6 and 0.7 m.y. ago, based on the Gulf of Mexico record, when, in fact, this interval of time is represented by nonglacial deposits in the study area. Both of these problems are removed by making the modifications outlined above in the interpretation of the paleotemperature record of the Gulf of Mexico.

TABLE II

Terminology of Pleistocene Volcanic Ash Deposits
From the Great Plains, United States

Ash Name	Reference Locality	Age Criterion (FT-glass)	Chemical Criteria (glass)	Source Area
Green Mountain Reservoir *	Near Green Mountain Reservoir, SE¼, Sec. 18, T. 2 S., R. 79 W. Summit County, Colorado	≈ 0.4 m.y.	≈ 0.3% Fe, 830 ppm Mn, 7 ppm Sm **	Bishop area, California **
Pearlette (restricted)	Cudahy Ash Mine; SW¼, Sec. 2, T. 31 S., R. 28 W., Meade County Kansas	≈ 0.6 m.y.	≈ 1.1% Fe, 280 ppm Mn, 12 ppm Sm	Yellowstone Park area, Wyoming and Idaho *
Hartford	SW¼NE¼, Sec. 11, T. 102 N., R. 51 W., Minnehaha County, South Dakota	≈ 0.7 m.y.	≈ 1.1% Fe, 280 ppm Mn, 13 ppm Sm	Yellowstone Park area, Wyoming and Idaho
Mount Clare	SE¼, Sec. 26, T. 3 N., R. 8 W. Nuckolls County, Nebraska	≈ 0.8 m.y.	≈ 0.6% Fe, 200 ppm Mn, 5 ppm Sm	Bishop area, California ***
Coleridge	NE¼NE¼, Sec. 11, T. 29 N., R. 1 E., Cedar County, Nebraska	≈ 1.2 m.y.	≈ 1.0% Fe, 240 ppm Mn, 11 ppm Sm	Yellowstone Park Area, Wyoming and Idaho *
Upper Borchers (provisional)	SESW, Sec. 16, T. 33 S., R. 28 W., Meade County, Kansas	≈ 1.2 m.y.	≈ 1.1% Fe, 504 ppm Mn, Sm not available	Jemez Mountains, New Mexico (?)
Guaje *	NW¼NE¼ (1) Block 3 of Eastland County School Lands (1) along Hwy 193 about 300 m west of east edge of Floydada SE quadrangle, Crosby County, Texas *	≈ 1.8 m.y.	≈ 1.0% Fe, 570 ppm Mn, 13 ppm Sm *	Jemez Mountains, New Mexico *
Borchers	NW¼NE¼, Sec. 21, T. 33 S., R. 28 W., Meade County, Kansas	≈ 2.0 m.y.	≈ 1.2% Fe, 280 ppm Mn, 14 ppm Sm	Yellowstone Park area, Wyoming and Idaho *
Arcadia Canal	Center E½NE¼NE¼SW¼, Sec. 5, T. 16 N., R. 15 W., Sherman County Nebraska	≈ 2.3 m.y.	≈ 1.3% Fe, 290 ppm Mn, Sm not available	Yellowstone Park area, Wyoming and Idaho (?)

* Izett and others, 1972

** Borchardt and others, 1972

*** Izett and others, 1970

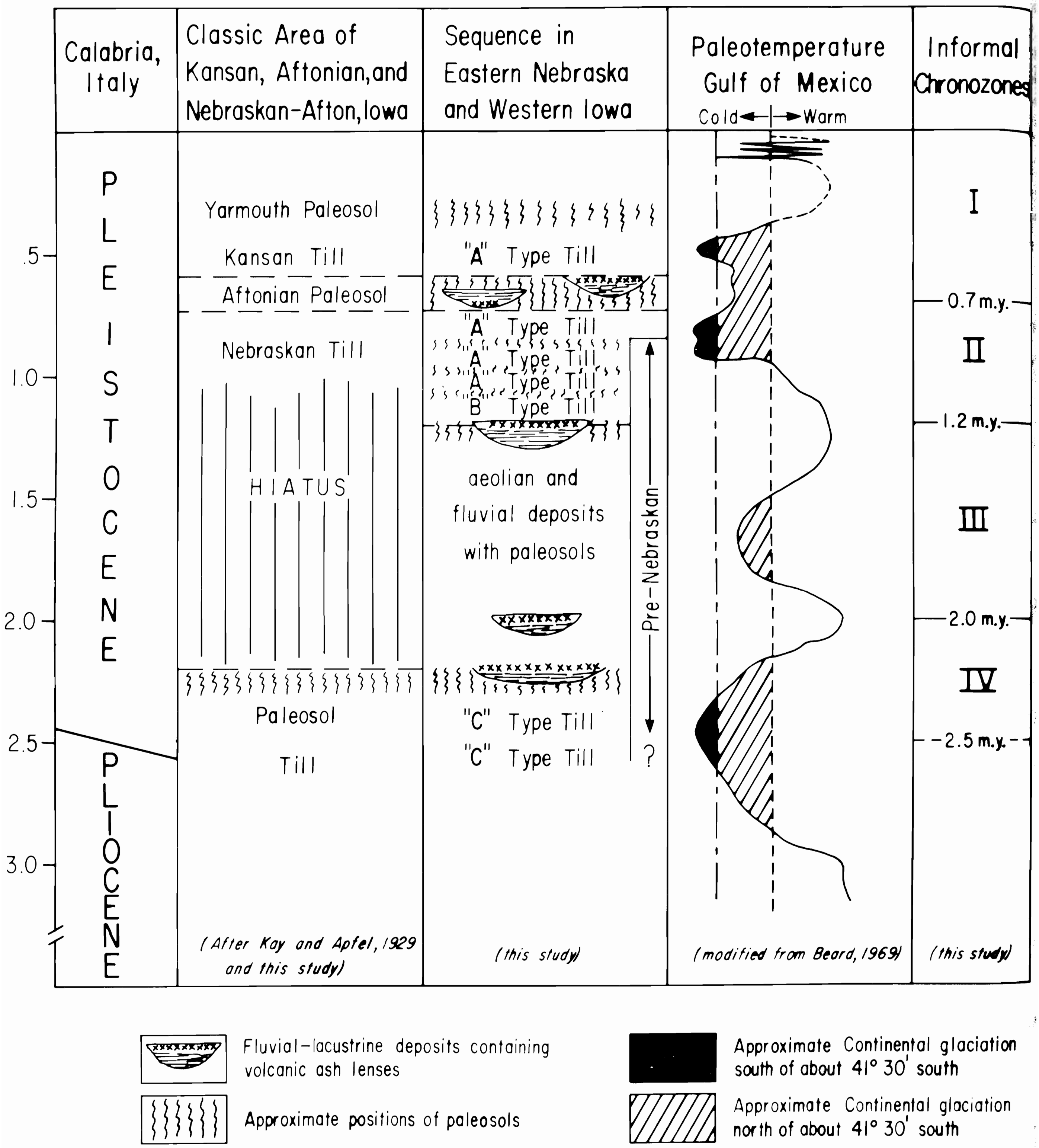

Figure 5. Comparison of chronologies of some Pleistocene deposits from North America and Italy. Informal chronozones are suggested for use in Nebraska and adjacent areas. See text for explanations. Chronology of Gulf of Mexico sequence provided by paleomagnetic dating. All other chronology provided by fission-track dating of volcanic ashes (glass).

NORTH AMERICAN ICE AGE DEPOSITS AND THE PLEISTOCENE

As shown in Figure 5 and discussed earlier, the date of 2.5 ± 0.1 m.y. for the volcanic ash in the Vrica section, Calabria, Italy, is herein considered a tentative minimum date for the beginning of the Pleistocene.

The paleotemperature record of the Gulf of Mexico (Beard, 1969) suggests the first late Cenozoic Ice Age in North America commenced about 2.8 m.y. ago, reached a maximum around 2.4 m.y. ago, and ended about 2.1 m.y. ago. Till in Nebraska and Iowa older than about 2.2 m.y. probably is contemporaneous with the maximum of the first cold cycle recorded in the Gulf of Mexico and, hence, about 2.4 m.y. old. If the date of 2.5 ± 0.1 m.y. for the Plio-Pleistocene boundary and the chronology of the Gulf of Mexico Paleotemperature curve are correct, this first Ice Age may span the Plio-Pleistocene boundary. However, the glacial deposits in Nebraska and Iowa may be entirely Pleistocene.

The second Ice Age occurred between about 1.9 and 1.5 m.y. ago. However, apparently it was not severe enough for glaciers to reach into Nebraska or central Iowa.

The third Ice Age occurred between about 1.0 to 0.4 m.y. ago. Glaciers invaded Nebraska and Iowa at least four times during this Ice Age, and periods between these advances were of sufficient duration for the formation of paleosols and gleys. The classic Nebraskan-Aftonian-Kansan sequence was deposited during this Ice Age.

The fourth Ice Age commenced about 100,000 years ago. Glacial deposits representing this Ice Age reached central Iowa but apparently did not enter Nebraska.

NOMENCLATURE OF PLEISTOCENE DEPOSITS

Pre-Wisconsinan Pleistocene stage terms have been applied conceptually—i.e., in a given region the oldest Pleistocene "cold" cycle has been considered "Nebraskan"; the first "warm" cycle, "Aftonian"; the second "cold" cycle, "Kansan"; and so on. This practice has resulted in overlapping time spans of stage terms as follows (Boellstorff, 1978a): "Nebraskan," 2.8 to 0.7 m.y.; "Aftonian," 2.0 to 0.6 m.y.; "Kansan," 1.7 to 0.5 m.y.; "Yarmouthian," 1.3 to 0.5 m.y.; "Illinoin," 0.8 to 0.25 m.y.; "Sangamonian," 0.4 to 0.25 m.y.

Because of the confusion generated by the overlapping usages of the classic North American Pleistocene stage terms and because ≃ 60 percent of the Pleistocene is older than the classic Nebraskan (Fig. 5), I have recommended that the stage terms be redefined or abandoned (Boellstorff, 1973, 1978a and b) and that in the interim informal chronozones be used as outlined below.

Chronozone IV:	2.0 m.y. to the base of the Pleistocene, here interpreted to be about 2.5 m.y.
Chronozone III:	1.2 m.y. to 2.0 m.y.
Chronozone II:	0.7 m.y. to 1.2 m.y.
Chronozone I:	recent to 0.7 m.y.

Chronozone I would include the Wisconsinan, Sangamonian, and Illinoian stages as currently used. This system would be more suitable for the study area where some glacial advances may have occurred but for which direct evidence is lacking and where considerable reliance must be placed on ash dates, detailed stratigraphic studies, and paleomagnetics.

As shown in Figure 5, ongoing research indicates a close correlation between the chronology of the paleotemperature record of the Gulf of Mexico and the chronology of glacial and nonglacial conditions in the central United States. Therefore, any redefinition of the North American Pleistocene stages should be based on the integration of the midcontinent and Gulf of Mexico records.

CHRONOLOGY OF SOME PRE-PLEISTOCENE LATE CENOZOIC DEPOSITS OF THE GREAT PLAINS

Studies of the late Tertiary sediments (mainly Ogallala Group) and their contained fauna and flora from the Great Plains have long been used in making interpretations of conditions leading up to the Ice Ages. A summary of fission-track ages (glass) of volcanic ashes associated with these deposits is presented in Figure 6. These dates indicate that alternative interpretations of the late Tertiary age stratigraphic and paleontologic records and of conditions leading up to the Ice Ages are in order.

In Nebraska, sediments of the Ogallala Group have long been considered Pliocene, even though Lugn (1939) thought this age assignment should be tentative because of the lack of agreement among stratigraphers and paleontologists concerning the criteria used to differentiate Miocene from Pliocene. The Ogallala Group sediments have been considered to represent the "latest" Tertiary aggradation of the Central Plains prior to uplift and associated climatic changes that inaugurated the Pleistocene (Schultz and Stout, 1945, 1948; Schultz, Tanner, and Martin, 1972). Furthermore, the Ogallala was considered to span the entire Pliocene epoch (Schultz and Stout, 1948; Tanner, 1975).

The upper formation in the Ogallala Group (the "Kimball Formation") and its contained fauna have been considered latest Pliocene (Schultz and Martin, 1970; Schultz and Stout, 1961; Schultz, Schultz, and Martin, 1970; Tanner, 1967). Schultz and Stout (1948) stated, "The mammals found

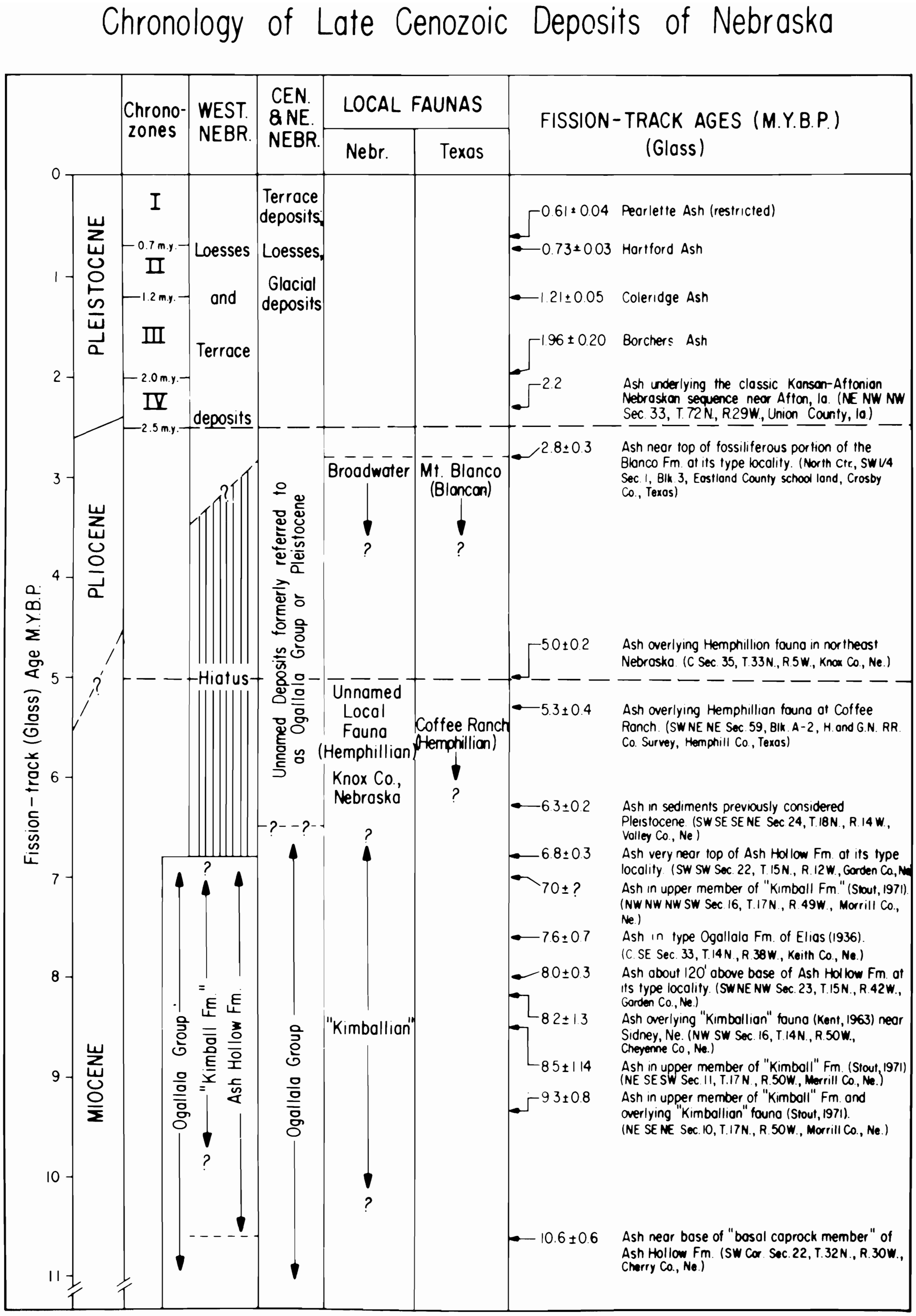

Figure 6. Chronology of some late Cenozoic sediments and faunas from the Great Plains, United States. Chronology provided by fission-track dating of volcanic ashes (glass).

in the Kimball-Sidney sediments are of a distinctive Pliocene type (closely related to those found in the underlying Ash Hollow Formation), and they differ markedly from the mammals found in the later Broadwater-Lisco deposits of the same area" (Barbour and Schultz, 1937; Schultz and Stout, 1948). The Broadwater Fauna was considered early Pleistocene in age. Apparently because Schultz and Stout (1948) considered the Ogallala Group sediments to span the entire Pliocene, they assigned a late Pliocene age to sediments and faunas ("Kimball Formation and Kimballian Fauna") at the top of the Ogallala Group (the Kimballian was informally introduced as a North American provincial mammal age by Schultz and Stout, 1961).

Schultz and Martin (1975) stated that "the Kimballian fauna from Nebraska differs from the Hemphillian fauna in that most of the known forms are markedly more advanced, but definitely pre-Blancan (Early Pleistocene)." This statement and the fission-track dates on volcanic ashes overlying "Kimballian" fauna and Hemphillian fauna (Fig. 6) are in contradiction.

Schultz and Stout (1948) recognized the existence of a significant lithologic and faunal break between the finer grained, carbonate-rich, latest Ogallala sediments ("Kimball Formation") and the coarse-grained, crystalline gravel deposits of the earliest Pleistocene (Broadwater Formation). As a measure of the temporal gap between these two sets of sediments, they concluded that "the interval apparently is not quite as long as the time which elapsed between Early and Medial Pleistocene."

The "Kimballian" has also been viewed as a period of climatic change and extinction because of the profound difference between the "Kimballian" faunas ("latest Pliocene") and the "early Pleistocene Broadwater fauna" (Schultz and Stout, 1948; Schultz, Schultz, and Martin, 1970; Schultz, Tanner, and Martin, 1972). Schultz and Stout (1948) state, "The faunal break between the Kimball and Broadwater formations is the most important one paleontologically in the Upper Tertiary and Pleistocene of western Nebraska (and Great Plains). It is the writers' opinion that this is the Pliocene-Pleistocene boundary."

As shown in Figure 6, fission-track dates indicate that Ogallala Group sediments, previously considered latest Pliocene in western Nebraska, are older than about 6.5 m.y. and that a hiatus of approximately 3 to 4 million years duration exists between these sediments and those considered early Pleistocene in eastern Nebraska. These dates indicate that sediments assigned to the "Kimball Formation" (Stout, 1971), the Ash Hollow Formation (type locality), and the Ogallala Formation (type locality—Elias, 1936) are contemporaneous.

This conclusion is supported by lithologic studies. Swinehart (1974) stated, "Attempts to correlate Ogallala sediments with the Kimball and Sidney units as established on outcrop have not proven feasible. These units do not appear to be valid lithostratigraphic units because they are not lithologically distinct and do not occupy consistent stratigraphic relationships." All these sediments, perhaps with the exception of local caliche deposits at or very near the topographic surface, are Miocene in age in terms of a Miocene/Pliocene boundary at 5.0 m.y., as indicated by Berggren and Van Couvering (1974).

As shown in Figure 6, ashes overlying "Kimballian" faunas are older than 7 m.y. and some are as old as 9.3 ± 0.8 m.y. Ashes overlying the type Hemphillian fauna at Coffee Ranch, Hemphill County, Texas, and fauna identified as Hemphillian in Knox County, Nebraska (Voorhies, 1977) date at 5.3 ± 0.4 and 5.0 ± 0.2 m.y., respectively. Apparently some "Kimballian" faunas must be Hemphillian or older.

An ash near the top of the stratal span of the Mount Blanco Fauna at its type locality is dated at 2.8 ± 0.3 m.y. This date indicates the Mount Blanco Fauna and its equivalents, such as the Broadwater and Rexroad faunas, may be of a similar Pliocene age. The time gap between the Broadwater Fauna (equivalent to the Mount Blanco and early Pleistocene in age, Schultz and Stout, 1948; Schultz and Martin, 1970, 1975) and some "Kimballian" faunas may be about 4 m.y.

The rapid extinction and climatic changes postulated by Schultz and Stout (1948) and considered "one of the events which marks the end of the Pliocene Epoch" (Schultz, Tanner, and Martin, 1972) was based on the marked differences between the "Kimballian" faunas and the "early Pleistocene" Broadwater Fauna. Fission-track ages suggest that these faunas are separated by 4 m.y. of time. Thus, the significance of the marked differences between these faunas needs to be re-evaluated.

Recently, sediments representing the 4 million year hiatus between sediments assigned a latest Pliocene age and those assigned an early Pleistocene age in western Nebraska (Fig. 6) have been identified in central and northeastern Nebraska by means of fission-track dating. Faunas from these sediments should prove to be younger than those assigned to the "Kimballian" from western Nebraska.

Interpretations of conditions leading up to continental glaciation in Nebraska have been derived largely from studies of faunas and sediments from what was considered to be a relatively complete sequence from latest Pliocene time ("Kimball Formation and Kimballian faunas") to early Pleistocene time (Broadwater Formation and Broadwater Faunas). The presence of a lengthy hiatus between these sediments and faunas was unrecognized. Therefore, these interpretations need to be re-evaluated.

In terms of 2.5 ± 0.1 m.y. date for the Plio-Pleistocene boundary, the Blanco, Broadwater, and equivalent faunas are

Pliocene in age. "Kimballian" faunas and Ogallala Group sediments are late Miocene in age if the date of 5 m.y. (Berggren and Van Couvering, 1974) is valid for the Miocene-Pliocene boundary.

It now appears that the sedimentary and faunal record spanning time from latest Miocene (> 5.0 m.y.) through the Pliocene (< 5.0 m.y. > 2.5 m.y.) and into the early Pleistocene (> 2.2 m.y.) is present in the central to eastern parts of Nebraska. It is here that studies of changing conditions leading up to Pleistocene time in Nebraska should be centered.

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